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Research paper

Analysis of simply supported wood beams at ambient and high temperatures

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Abstract

The main objective of this work is to present a methodology for safety analysis of simply supported wood beams at ambient and high temperatures with a concentrated load at mid-span. Sixteen different beam configurations will be studied. All calculations were conducted according the Eurocode 5, part 1-1 and part 1-2. During this study will be analyzed the safe load bearing capacity according standards and compared with the elastic and plastic load from beam theory. The beam theory can provide sufficient accuracy up to the point of instability. The standard methods are generally conservative and they are suitable to be used for design purposes with safety. The studied beam cross sections will be in glued laminated wood, as yellow birch, with characteristics equals to a Glulam GL28H.

Keywords: *Wood, Beam, Temperature, Safety, Load bearing capacity.*

1. Introduction

Wood is a composite material and it is generally anisotropic, heterogeneous and porous. The safety of structural wood beams depends of the corrected determined load bearing capacity.

Different wood cross-sections can be manufactured, depending on the strength and stiffness requirements. Architects and engineers have many opportunities to design their own forms and shapes, for different ranging and complex beams configurations. For this reason, glulam can more easily adapted to market and satisfy the structural demands, [1]. Commonly used cross-sections are rectangular. Also the material mechanical properties depend upon grain orientation, and are affected by moisture content, [2]. At high temperatures, the wood mechanical behavior varies. The increase of temperature influences the progressive degradation of mechanical material properties. Apart from reducing of the cross-section, the degradation of mechanical properties contributes to the loss of structural bearing capacity. The Eurocode 5, part 1-2, (2003) [3] considers a reduction of mechanical properties in order of 20% compared to the same material at ambient temperature. Consequently, the strength of structural wood beams decreases when is exposed to high temperatures, such as the fire situation [4].

This work describes the performance in structural wood beams. It intends to compile design formulas for further discussions and enhancements to structural safety of wood beams under thermal and mechanical loading conditions. The authors of this work have published different articles related to this subject [5-9].

The main objectives of this work is to evaluate the load bearing capacity in a wide range of selected rectangular cross-section wood beams, when subjected to ambient or elevated temperatures.

At ambient temperature, following the safety design considerations according the Eurocode 5, part 1-1, [10] and comparing with elastic and plastic beam theory. At elevated temperatures, following the safety design considerations according the Eurocode 5, part 1-2, [3] introducing the residual cross-section effect. For this calculation to evaluate and considering the charring layer effect in the cross section reduction for a three sides of fire exposure. Char has no significant strength, and when grows the beam load bearing capacity reduces. All obtained results are based on a set of simple calculation methods for simply supported beams, under the effect of a concentrated load at mid-span.

2. Safety design considerations

For a realistic analysis of the load bearing capacity of wood elements at ambient, as well as at high temperatures, an accurate understanding about strength properties is required [11].

In this work, the bending strength of the Glulam GL28H is equal to 28MPa, where the yield stress ($f_{m,k}$) in tensile parallel to grain is equal to 22,3MPa, (EN 14080:2013-09). The mean value of the modulus of elasticity is equal to 12600MPa and the density 425kg/m^3.

The beam theory is used in the design and analysis of a wide range of structural elements. According the elementary elastic beam theory, it will assume that the beam has a longitudinal symmetry plane, and the load and supports are also symmetric about this plane. According this conditions, no tendency to twist and the beam supports the load by bending only. Due the applied load condition, in the top the fibres contract in length and the fibres in the bottom extend. Over any beam cross-section, the normal and shear stresses occur. When a beam is in pure bending, with shear force everywhere zero, the beam theory is exact. In elastic behaviour the bending moment causes stresses less than the yield stress ($f_{m,k}$) of the material. The maximum elastic force ($Fd_{,el}$) that a

beam with a length (L) could support is assumed to equal the load that caused a yield stress in the structure.
When the bending moment form a plastic hinge in any particular beam cross section, the required value is the collapse load ($Fd_{,pl}$), where the ratio between of the collapse to the working force is the load factor. In plastic design this factor is used instead of the normal safety factor, and for a rectangular cross section beams are equal to 1.5. For this situation, the applied bending moment causes the yield stress in all fibres to the beam cross section, where the stresses remain constant and it is termed a plastic hinge. The plastic theory implies that cross sections that have been stressed to yield and they cannot more resist any additional stresses and the structure is geometrically unstable.
The design wood structures shall be in accordance with Eurocode 5. The design force (Fd) value shall be calculated using partial factors taking account the material property, the load effect duration and moisture content. In fire situations, the wood cross section forms outside, an insulating char layer and protects the section core. Thus, wood beams can be designed so that sufficient section remains to sustain the load bearing for a required time fire exposure.

2.1. Simply supported wood beams at ambient temperature under a concentrated load at mid-span

At ambient temperatures, a simply supported beam, with a rectangular cross-section (where B is the breadth and D is the depth D), Figures 1 and 2, will be used to calculate the design force F_d.

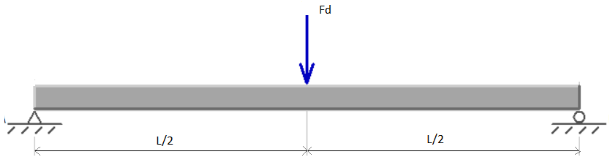

Fig. 1: Simply supported beam at ambient temperature.

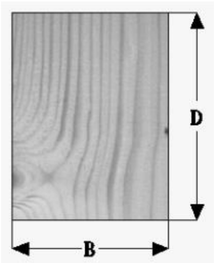

Fig. 2: Rectangular cross section

The maximum elastic force ($Fd_{,el}$) at mid-span could be calculated as in (1).

$$Fd_{,el} = \frac{2 \times f_{m.k} \times B \times D^2}{3 \times L} \tag{1}$$

The collapse force ($Fd_{,pl}$) is calculated according the equation (2).

$$Fd_{,pl} = 1{,}5 \times Fd_{,el} \tag{2}$$

According Eurocode 5, part 1-1, [10], considering the partial factors (k_{mod}, k_h, γ_m), respectively, the modification factor for medium term load duration, depth modification factor for Glulam and the material partial safety factor for glued laminated timber, equation (3) permits the calculation of design force F_d according the bending strength $f_{m,k}$ for Glulam.

$$Fd = \frac{k_{mod} \times (f_{m.k} \times k_h)}{\gamma_m} \times \frac{2 \times B \times D^2}{3 \times L} \tag{3}$$

2.2. Simply supported wood beams at high temperatures under a concentrated load at mid-span

At high temperatures the initial breadth B and depth D of a wood beam member are reduced to b and d respectively, according the three sides exposed to fire (two lateral and bottom side), Figure 3 and Figure 4.
The calculation of the design force in fire $F_{d,f}$ is according the reduced cross section method, from Eurocode 5, part 1-2, [3].
The charring depth is the distance between the outer surface of the original cross section and the char line. The charring reduces the beam cross section. Charring rate generally refers to the linear rate at which wood is converted to char [12]. Expressions for charring rate are referred by different investigators, based on many experimental studies, and also given in the Eurocode 5, part 1-2 [3], [13], as in (4) for the design charring depth ($d_{char,n}$), design charring rate (β_n) at given time from start of charring in minutes (t).

$$d_{char,n} = \beta_n \times t \tag{4}$$

There are two different charring rates depending on whether the cross section is exposed to fire from one (β_0) or multiple sides (β_n). For structural elements exposed to fire on more than one side, the effective charring depth (d_{ef}) is calculated according equation (5), [3], [13], where d_0 is equal to 7mm, considered as the depth of layer assumed zero strength and stiffness, and (k_0) is given in table 1 [13].

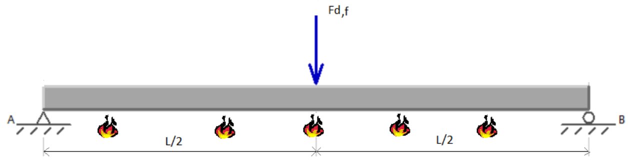

Fig. 3: Simply supported beam at high temperature.

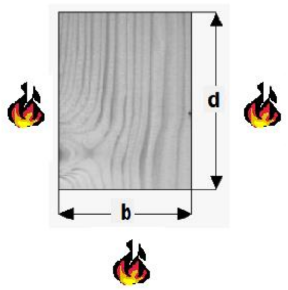

Fig. 4: Reduced rectangular cross section

$$d_{ef} = d_{char,n} + k_0 \times d_0 \tag{5}$$

Table 1: Determination of k_0 for unprotected surfaces with time (t, min)

time, min	k_0
t ≤ 20 minutes	t / 20
t > 20 minutes	1,0

For unprotected surfaces, k_0, should be determined according table 1. If the surfaces are protected with tchar ≥ 20 min, it should be assumed that time varies between 0 and 1, and for values with thar ≤ 20 min table 1 is applied, [3].
In Eurocode 5, part 1-2 [3], the design charring rate depends of the wood specie (hardwoods and softwoods) and its density, according the fire exposure in one-dimensional or more than one side.
In the worked examples, for a glued laminated timber with the density for GL28h, a charring rate equal to 0,7mm/min was considered.
In all examples the calculation of the reduced cross section will be considered according the upper face of the beams protected and the other three sides (two lateral and bottom) exposed to fire.

The residual cross section is rectangular in shape during fire exposure.
The effective residual section will be measured according (6) and (7) and its assumed that the strength and stiffness properties retains appropriate to the service class at normal temperature [13], due the core section remains intact.

$$b = B - 2 \times d_{ef} \tag{6}$$

$$d = D - d_{ef} \tag{7}$$

Using the reduced cross section method from Eurocode 5, part 1-2, [3], and considering the partial factors ($k_{mod,fi}$, k_{fi}, $\gamma_{m,fi}$), respectively, the modification factor for the fire design situation, coefficient for Glulam strength properties and the partial safety factor for timber in fire, equation (8) permits the calculation of design force in fire $F_{d,f}$ in accordance with the bending strength $f_{m,k}$ for Glulam.

$$Fd,_{f} = \frac{k_{\mathrm{mod},fi} \times (f_{m.k} \times k_{fi})}{\gamma_{m,fi}} \times \frac{2 \times b \times d^2}{0,6 \times 3 \times L} \tag{8}$$

3. Worked examples

All examples are present in tables 2 and 3, with all analytical concepts introduced through a developed spreadsheet.
Table 2 presents the cross section considered in all worked examples and the results for the load bearing capacity at ambient temperature considering all previous calculations in 2.1.
Table 3 represents the reduced cross section for all examples, considering a fire exposure during 30min on three sides, and the respectively load bearing capacity calculation in fire situation, following the methodology in 2.2.

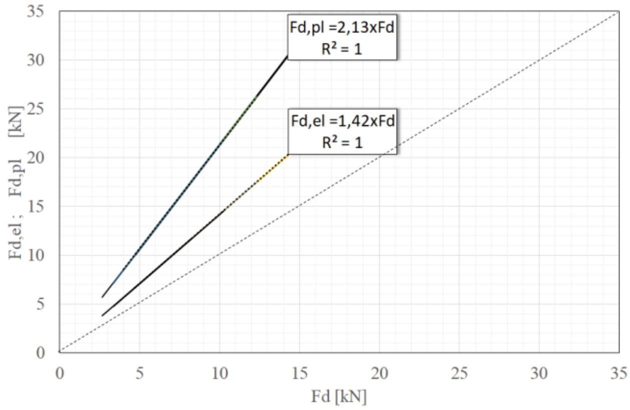

Fig. 5: Relation between the load bearing capacity from elastic and plastic theory with design force.

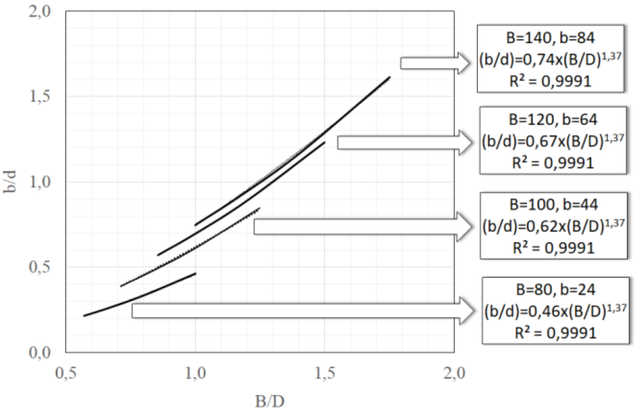

Fig. 6: Relation between wood beam geometry at ambient and high temperature for fire exposure during 30min.

Table 2: Load bearing capacity at ambient temperature

Wood beam geometry, mm			Load bearing capacity at ambient temperature, kN		
B	D	L	Fd	$Fd,_{el}$	$Fd,_{pl}$
80	80	2000	2,679	3,806	5,709
80	100	2000	4,187	5,947	8,920
80	120	2000	6,028	8,563	12,844
80	140	2000	8,205	11,655	17,483
100	80	2000	3,349	4,757	7,136
100	100	2000	5,233	7,433	11,150
100	120	2000	7,536	10,704	16,056
100	140	2000	10,257	14,569	21,854
120	80	2000	4,019	5,709	8,563
120	100	2000	6,280	8,920	13,380
120	120	2000	9,043	12,845	19,267
120	140	2000	12,308	17,483	26,225
140	80	2000	4,689	6,660	9,990
140	100	2000	7,326	10,407	15,610
140	120	2000	10,550	14,986	22,478
140	140	2000	14,360	20,397	30,596

Table 3: Load bearing capacity at high temperature

Wood beam geometry, mm Fire exposure, time=30min			Load bearing capacity at high temperature, kN
b	d	L	$Fd,_{f}$
24	52	2000	0,925
24	72	2000	1,773
24	92	2000	2,894
24	112	2000	4,289
44	52	2000	1,695
44	72	2000	3,250
44	92	2000	5,306
44	112	2000	7,864
64	52	2000	2,466
64	72	2000	4,727
64	92	2000	7,718
64	112	2000	11,438
84	52	2000	3,236
84	72	2000	6,204
84	92	2000	10,129
84	112	2000	15,012

With the values presented in table 2, Fig. 5 represents the relation between the load bearing capacity according elastic and plastic theory with the design force at ambient temperature.
According the results, the elastic load represents a value higher than 42% when compared with the design force, which depends of the included partial safety factors. In simultaneous, the calculation of the collapse force represents more than 113% of the safety design force.
The comparison between the cross section before (B/D) and after (b/d) fire exposure of 30min is obtained in Fig. 6.

The comparison between the cross section before (B/D) and after (b/d) fire exposure of 30min is obtained in Fig. 6.
Different equations from power trend line were obtained, which permit the calculation for dimensions, according the breadth cross section range values. These type of curved lines are the best used with data set increase at a specific rate. It is notice that R-squared value is 0,9991, which is a good fit of the curved data line. All power equations have a constant exponent value equal to 1,37. When the wood beam cross section decreases the curve presents a lower slope, as shown by the multiplier factor.

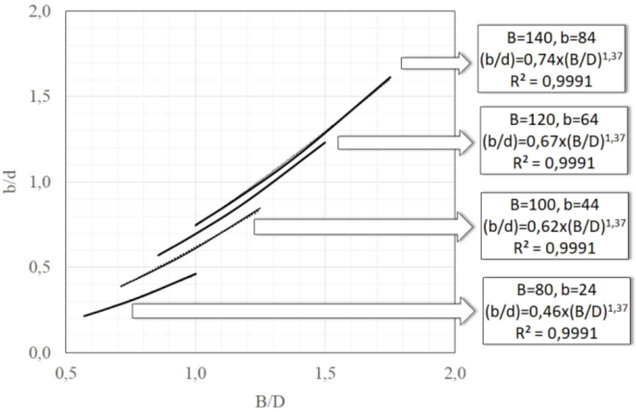

Fig. 6: Relation between wood beam geometry at ambient and high temperature for fire exposure during 30min.

Fig.7 presents the comparison between the design force at ambient and fire exposure of 30min.

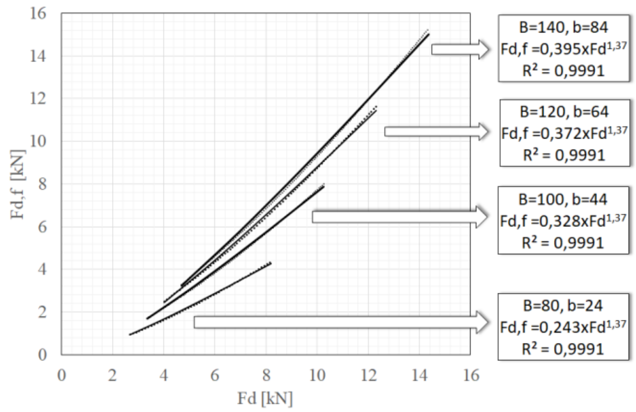

Fig. 7: Relation between the design force at ambient temperature and the design force in fire for 30min.

The equations are also obtained by the power trend line and with the same constant exponent value, as the previous. Also, there is a decrease in the fire design load for smaller cross sections. For higher cross sections the design load has an exponential growth behaviour. For higher cross sections the fire design load increase when compared with the design load at ambient temperature.

4. Conclusion

In this work the results presented were conducted according the elastic and plastic beam theory, and also using simplified equations from Eurocode 5, part 1-1 [10] and part 1-2 [3]. A worksheet considering all parameters was developed, which permits verify the load-bearing capacity of the wood beams, at ambient and high temperature.

The results were presented in different tables and graphics, according the design equations. The results show that the load bearing capacity of wood beams at high temperatures decreases because of reduction of cross section.

For the structural analysis, a linear beam theory can provide sufficient accuracy up to the point of instability. The methods based on standard are generally conservative and they are suitable to be used for design purposes with more safety.

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